

GAMMA RAY BURSTS AS COSMOLOGICAL PROBES*

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We discuss the prospects of using Gamma Ray Bursts (GRBs) as high-redshift distance estimators, and consider their use in the study of two dark energy models, the Generalized Chaplygin Gas (GCG), a model for the unification of dark energy and dark matter, and the Λ CDM model, a model where a generic dark energy fluid like component is described by the equation of state, $p = \omega\rho$. Given that the GRBs range of redshifts is rather high, it turns out that they are not very sensitive to the dark energy component, being however, fairly good estimators of the amount of dark matter in the Universe.

1. Introduction

Recently, there has been a flurry of activity about the prospect use of GRBs as cosmological probes¹. In the original proposal², it has been suggested that the magnitude versus redshift plot, could be extended to a redshift up to $z \simeq 4.5$ via correlations found between the isotropic equivalent luminosity, L_{iso} , and two GRB observables, namely the time lag (τ_{lag}) and variability (V). The isotropic equivalent luminosity is the inferred luminosity (energy emitted per unit time) of a GRB if all its energy is radiated isotropically, the time lag measures the time offset between high- and low-energy arriving GRB photons, while the variability is a measure of the complexity of the GRB light curve. Unfortunately, these correlations are affected by a large statistical (or intrinsic) scatter. This statistical spread affects not only the cosmological precision via its direct statistical contribution to the distance modulus uncertainty, σ_μ , but also through the calibration uncertainty given that the suitable GRB sample with known redshift is rather

*Talk presented by one of us (P.T.S.) at the XV Encontro Nacional de Astronomia e Astrofísica, Lisbon, Portugal, 28-30 July 2005.

small. In what follows we show that a relatively small sample of GRBs with low redshifts is sufficient to greatly reduce the systematic uncertainty thanks to a more robust and precise calibration.

More recently, a new correlation was suggested³, which is subjected to a much smaller statistical scatter. The so-called Ghirlanda relation, is a correlation between the peak energy of the gamma-ray spectrum, E_{peak} (in the $\nu - \nu F_{\nu}$ plot), and the corrected collimation energy emitted in gamma-rays, E_{γ} . This collimation energy is a measure of the energy released by a GRB taking into account that the energy is beamed into a narrow jet. Unlike the $L_{iso} - \tau$ and $L_{iso} - V$ relations, the Ghirlanda relation is not affected by large statistical uncertainties, but is dependent on poorly constrained quantities related to the properties of the medium around the burst.

Another difficulty involving GRBs is that they tend to occur at rather large distances, which makes it impossible to calibrate any relationship between the relevant variables in a way that is independent from the cosmological model. The method that is usually employed consist in fitting both, the cosmological *and* the calibration parameters, and then use statistical techniques to remove the undesired parameters. In here, we follow a different procedure^{1,4}. We consider a luminosity distance for $z < 1.5$ that is measured by SNe Ia, and divide the GRBs sample in two sets; the low redshift sample, with $z < 1.5$, and the high redshift one, with $z > 1.5$. Since the luminosity distance of GRBs in the range $z < 1.5$ is now known, one can calibrate the luminosity estimators independently of the cosmological parameters and use the high redshift sample as a probe to dark energy and dark matter models.

We have analyzed the use of these several correlations in the study of the GCG, a model that unifies the dark energy and dark matter in a single fluid⁵ through the equation of state $p_{ch} = -A/\rho_{ch}^{\alpha}$, where A and α are positive constants. The case $\alpha = 1$ describes the the Chaplygin gas, that arises in different theoretical scenarios. If the total amount of matter is fixed, there are only two free variables, A and α , although it is more customary to use the quantity $A_s \equiv A/\rho_{ch,0}^{1+\alpha}$ instead of A . Thus, we consider two free parameters, α and A_s . A great deal of effort has been recently devoted to constrain the GCG model parameters⁶, which include, for instance, gravitational lensing⁷ and cosmic topology⁸.

In addition to the GCG model, we also study the more conventional flat Λ CDM model. Likewise the GCG model, the Λ CDM model is also described by two free parameters, the parameter, ω , of the dark energy equation of state $p = \omega\rho$, and the fraction of of dark matter, Ω_m . The test

of these models is particularly interesting since it is known that they are degenerate for redshifts $z < 1$ ^{9,10}.

2. Variability and Time Lag as Luminosity Estimators

Our work can be divided in two parts. First, we test the calibration procedure. The small sample of GRBs with measured redshifts means that at present the calibration is rather poor. We assess the gain in calibrating the relations with larger samples by generating three mock samples and by performing their calibration. We find that a calibration done with 40 GRBs will greatly improve the previous results, decreasing σ_μ , by close to half, yielding $\sigma_\mu = 0.68$. However, by increasing the calibration sample to 100 GRBs the resulting decrease is just marginal, suggesting that is not much of a use to consider very large calibration samples. Its worth noting that a sample of about 40 GRBs may be available in the near future, thanks to the *Swift* satellite. We also find that despite the large statistical scatter, thanks to the improved calibration, the uncertainty for this estimator becomes quite close to that of the Ghirlanda relation, that is, $\sigma_\mu = 0.5$.

We have then examined how GRBs fared when used to constrain both models under consideration. Somewhat against our expectation, we found that GRBs are not very suited to study the GCG model. The results for the XCDM model are more promising, however we find that GRBs are sensitive essentially to Ω_m , and very weakly sensitive to ω . The reason for these results is the redshift range where GRBs lay. We have verified that when using a sample that includes 100 with $z < 1.5$ GRBs, the constraints on the XCDM model were much better, as is depicted in Fig. 1. These results were found using the minimal $\sigma_\mu = 0.66$. This uncertainty is essentially due to the statistical component, and hence it cannot be reduced by better calibration or data.

We also tested the use of the Ghirlanda relations, which is intrinsically more precise. As before, we find that characteristic feature of GRBs of having rather high redshifts, make them somewhat unsuitable to study dark energy models, even the GCG one. One finds that results are better if one uses the Ghirlanda relations, but in what concerns dark energy models not crucially. It should be noted that data quality and statistics will greatly improve in the future thanks to *Swift* and *HETE 2* experiments.

Nevertheless, our main conclusion is that although GRBs are poor dark energy probes, for $z > 1.5$, the luminosity distance is quite sensitive to the dominating component at the time. For the XCDM model, this is dark

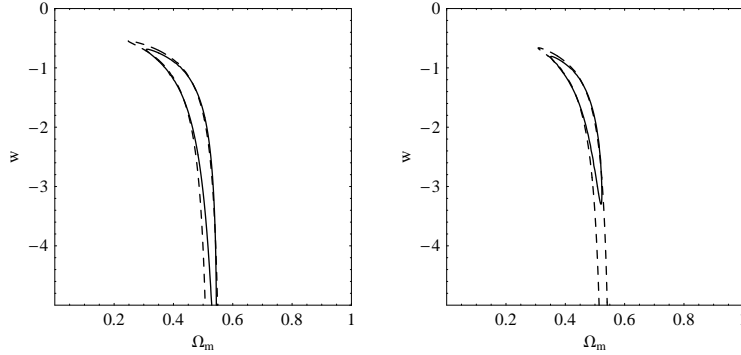


Figure 1. Confidence regions found for the XCDM model. The solid lines show the 68% CL regions obtained through a sample of 100 low-redshift ($z < 1.5$) and 400 high-redshift ($z > 1.5$) GRBs, while the dashed lines show the 68% CL constraints for a sample made up of 500 high-redshift GRBs only. On the left figure, the $\tau - L_{iso}$ and $V - L_{iso}$ relations have been used, while on the right one the Ghirlanda relation was employed.

matter, and we find that the amount of dark matter can be remarkably constrained. For the GCG model, on the other hand, it turns out that what arises is a combination of A_s and α parameters, and data cannot lift the degeneracy on α . Actually, this feature is encountered in various phenomenological studies of the GCG, the only exception being on data from large scale structure formation¹¹.

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